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A Study of the Application of Advanced
Control Systems to Fusion Experiments and Reactors

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Preface

This interim report summarizes the work to date toward the formulation of an advanced control system concept for large scale magnetically confined thermonuclear fusion devices. These large scale devices will be built in the coming decades for DT burning and possible power production. The work to date has been concentrated in three major areas:

- a) General control studies and identification of control issues.
- b) Exploration of possible direct interactions with AEC National Laboratories.
- c) Identification of simulation requirements to support control studies*.

Task (a) was an introductory effort providing a framework for the effort involved in tasks (b) and (c), and directing attention to certain specific problems which are discussed in the appendices of this report. Tasks (b) and (c) produced the main body of this report, a preliminary set of recommendations both for long term and for the immediate future. These are presented in Sections 2 through 5.

Section 2 defines the scale of the instrumentation and control system being proposed and shows why it is a desirable and practical system in which to invest. The proposed system is described by a name and acronym that provide a convenient framework for describing the remaining contents of the report. The acronym is MIMICS, standing for Modular Integrated Multifunction Interactive Control System.

Section 3 presents a representative preliminary system design in which a number of modular controllers are integrated through a central processor into a single system that performs a multitude of functions associated with sensing, data processing, and control. Control problems related to the particular modules are also discussed.

Reported in April

*Supported internally.

The task of making a control system interactive is addressed in Section 4. The convenience of the operator is served with an appropriately designed control console and data display unit, and, most importantly, by a complete system simulator in the form of a computer code with various plug-in subroutines.

The final Section, 5, concerns control system problems related to component failure. The first subsection concerns minimization of such failures through reliability and quality assurance procedures. But they cannot be absolutely prevented, so the following subsections address the issues of failure detection and control under conditions requiring either transfer to redundant components or scram procedures.

The appendices concern specific simulation and control problems that were discussed during visits to plasma research centers. The simulation problems relate to plasma modeling, magnetic field configurations, and neutral beams. The control problems relate to plasma positioning, instability control in the ATC, and feedback control of the UWMAK device. Specific system-wide control problems are cataloged in the last appendix.

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1.0 Introduction

1.1 Background

There has been a natural and continuing evolution of both instrumentation and control systems for experimental fusion devices. As these devices has grown in size and complexity, there has been a corresponding growth in the sophistication, flexibility and usefulness of the instrumentation and control systems. The increased cost of such systems has been more than offset by the increased physics output and reduced downtime for devices using advanced controls and instrumentation. Machine sizes will continue to grow, and instrumentation will have greater demands placed on it, as experimental sophistication increases.

The advent of large scale experimental fusion devices*, including tokamaks, θ pinch and mirror machines, will be accompanied by comprehensive on-line data acquisition and processing facility, to service experiments, along the lines of the DAS 1800 at PPPL. In addition, the complexity of the control systems will demand programmable central controllers, which are inherently digital in design and whose information channels may be common to or parallel with the experimental sensory channels. In view of the high initial cost of such facilities, the need to support several different types of devices and accommodate a large unforeseen set of experimental needs, CSDL has been examining the desirability of a single multi-purpose Integrated Modular Interactive Control System to meet all the needs of large fusion devices. This report attempts to outline the general features of such a system and suggests areas where further work is required.

Specifically the studies reported herein recognize and exploit digital technology in configuring centralized data acquisition and control systems.

This trend toward increasing reliance on digital instrumentation has been evident for some time both in high energy physics experiments, where local minicomputers are in common use for data recoding and control, and

* 1978-80 Design, generation after PLT, requiring ~ \$100 M⁺ Capital outlay. Includes devices such as Wetwood Burner, PDX, and Doublet 3.

in the operation of large particle accelerators such as SLAC and Fermi^{*} National Accelerator⁽¹⁾⁽²⁾ where both local and central computers are employed for control. In general the operation of plasma confinement devices tends to be more complex than these accelerators; hence, arguments for employment of general purpose computers for many of these functions may be more justifiable.

More recently, the potential for digital control of fusion devices has been recognized with the introduction of the DAS/IBM 1800 for data acquisition or control functions (but not both) for the PPPL FM1, ST, and ATC devices⁽³⁾. PPPL employed the DAS/1800 for control because the high degree of subsystem interdependence in the FM1 required supervision by a central controller which could integrate about twenty subsystems into a single control system. This role was ideal for a digital processor which has flexibility and programmability and can generate the status data necessary for proper control. Digital technology will be an adjunct to existing analog instrumentation, such as drum storage, which is used for signal recording and playback to experimenters, prior to digital storage and processing of selected portions. After this initial screening of test results, the desired data is stored in digital form on tape and can then be further analyzed in off-line facilities.

The likely role of digital techniques is suggested in the candidate reference fusion control system described in Section 3. In this scheme, processing facilities and sensors are largely shared by the experiments and the control system, with a gain in economy, diagnostic capability, and real time data handling capacity. With the suggested arrangement, system checks via selected channels and other validation tests are readily available on-line, between machine pulses, by inserting pilot signals as close to the sensors as possible. Similarly, real time display of state variables in the proposed design will enhance machine operation and contribute to greater machine availability.

^{*} formerly the National Accelerator Laboratory, Batavia, Ill.

In the suggested configuration, use is made of local digital controllers for individual subsystems, as well as a central processor for overall supervision. This architecture allows for remoting subsystems, provides either automatic or semi-automatic options, and provides a degree of backup in event of partial or transient failures in the subsystem. The central processor is expected to be dual redundant and thus not readily susceptible to outages. This arrangement is currently in use in military communications where a highly reliable central processor system is required⁽⁴⁾. Where dual redundant central processors are used, data is written into each memory simultaneously. Also, each machine is fully programmed and can be reloaded from disk or tape. With the proposed structure a single machine is controlling; the standby machine assumes control when self tests internal to the primary controller are negative.*

Application of modern computer techniques is further encouraged by recent progress in computer reliability and validated software development, both pioneered at CSDL. With these important developments the previous advantage of "hard wired" logic has all but evaporated, particularly when the computer's superior data handling and diagnostic characteristics are factored in. (Hard wired memories are cumbersome.) Future experiments will see special purpose logic doing "front end" fast processing, with the general purpose machines providing most other functions.

1.2 Significance of Current Fusion Device Digital Experience

Recent experience in computer based central data acquisition systems lends credence to the concept discussed in this document of integrating control and instrumentation systems, recognizing that these are at present rigidly segregated. The value of the computer data acquisition function has been well demonstrated by the DAS/1800 system now in use for the ST, FM-1, and ATC fusion devices⁽⁵⁾.

* The standby processor can perform additional tests, check the primary decisions, and perform background data processing.

Some of the advantages of this system are: on-line data acquisition, analysis, and display, real time analysis support to experiments, and background data analysis capability. In addition, the system is capable of on-the-fly program changes and can be programmed directly by experimenters. With the 1800, data is available to the user-physicist via a memoscope display.

These advantages have been borne out by specific computations and graphical displays provided to experiments, including:

- a. Langmuir probe current vs. probe position and time plots (FM1)
- b. Graphs of Langmuir probe signal fluctuation vs. time (FM1)
- c. Displays of radial plasma position vs. time (ATC)
- d. Ion temperature measurements, by measuring and plotting charge exchange neutrals flux intensity vs. energy. This requires a least squares to fit to a set of points (ATC)
- e. Measurement of magnetic properties of plasma instabilities, involving 100 khz sampling of seven channels (ATC)
- f. Calculation of X Ray spectra by unfolding bremsstrahlung data from a pulse height analyzer and applying normalization factors
- g. Thomson Scattering experiment on-line data processing, requiring readings from eight photomultipliers, application of normalization and correction factors, and plots and storage of data.

All of the above functions would not have been possible without the 1800 central data acquisition/ processing facility, although selected portions may be feasible for minicomputers dedicated to individual experiments. The application of the same 1800 system to digital control⁽³⁾, a separate activity limited to the FM1, illustrates the central controller as an integrating and supervising element of the control system.

The successful use of the same processing system for both data acquisition and control suggests that an integrated central control/instrumentation system is an appropriate consideration for fusion devices in the CTR program. At the same time the well developed trend to employ minicomputers for individual experiments and subsystems can not be easily overlooked in view of the desirable redundancy and operational independence available with that structure.

The studies suggested in this report will let the consideration of central vs. multi minicomputers use be determined by optimum allocation of functions to the system or subsystem levels rather than rely on any preconceived notions about optimum structure. Since the requirements vary between devices and change for a single device with time, a single modular design accommodating these several fusion systems and having operational flexibility, is probably indicated. Conceivably, an organization utilizing both the central processor at the system level and miniprocessors at the subsystem level is possible in many cases.

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2.0 Modular Integrated Multifunction Interactive Control System (MIMICS)

This section, together with Section 3.0, describes the principle features of the suggested instrumentation and control system. It should be emphasized that while alternatives are also being considered, including decentralized control, separate data acquisition, etc. the non-central control concept is seen at this time to lack the basic capability of supervising the highly interactive subsystems of the plasma containment device; i. e., many of the subsystems, through separately identified, tend to interact strongly and should be under single supervision. For this reason a structure for the control system featuring a single central control unit is judged to be most appropriate. Within this control framework the proposed structure affords maximum flexibility.

In particular, with the proposed concept, detailed coordination and control can be delegated to specific subsystem controllers, thus preserving many of the desirable characteristics of a decentralized approach.

MIMICS is a modular, integrated, multifunction, interactive control system generally composed of standard modules which, taken in different combinations, will support several different experimental devices. MIMICS makes use of the fact that there are common elements to the various magnetic confinement schemes including magnet systems, vacuum systems, plasma diagnostics, neutral beam injectors, etc; elements which are different from device to device are constructed from the same family of modules, whose interfaces (signal levels, etc) are compatible. Substantial economy and time savings can be expected from the use of a single system whose one time costs^{*} are spread over many applications. The various modules are integrated into a flexible system containing both central and remote processors and both digital and analog elements. A problem for further study is the optimum partitioning of modules.

Module types would include processing, display, data buffering, sequencing, signal conditioning, and other digital processing modules. Also included would be failure detection and fault isolation modules to identify both major and minor failures. These systems would then activate either redundancy management systems or emergency scram systems depending on the severity of the failure. These systems would be designed

* includes both Longlead engineering development and capital outlays.

to maximize personnel safety and equipment integrity while minimizing down time and experimental data loss.

The proposed system is multifunction in the sense that it combines the functions of diagnostics, control, plant monitoring, data processing, data storage, data display, simulation, failure detection, redundancy management and emergency scram. Many of the same components can be used to some degree for more than one function. For example the plasma diagnostic instrumentation can be used both as a source of experimental data and as sensors for the control system. The desirable extent of this sharing is currently being studied.

MIMICS is interactive in the sense that the plasma parameters for each shot may be predicted by the operator utilizing both the experimental results of the previous shots and fast computer simulation. These features will help to maximize the operators control over the experiment. The control variables and output variables will be carefully selected so as to increase experimental utility and flexibility. For example a single knob may control several machine parameters and allow systematic variation of a plasma parameter. Feedback control might be desired to hold the plasma parameters constant during a shot or to enlarge the stable operating regimes of a given device.

The proposed control system would include a computer simulation of the device which would provide relatively crude but rapid simulation of the plasma. It could be used in between shots by the operator to help select parameters for succeeding shots.

MIMICS appears to be a logical evolution from current control systems. Its initial cost may be higher than other approaches but it is expected to be cost effective in terms of increased experimental utility. As this type of systematic approach is applied to more devices it should provide real long term cost savings as well as greatly enhanced control over the experiment.

FIGURE 1

3.0 Preliminary System Concept for MIMICS

One of the problems associated with the design of an interactive control system for a large-scale fusion experiment involves the selection of a system structure. An example of a structure which meets the general aims of MIMICS is shown in Figure 1. The hierarchy of this structure places the central processor-controller at the highest level. The central processor-controller maintains a system overview, checks secondary processors for proper function, provides an interface for the subsystems, maintains safety standards, coordinates plasma creation, including transient operations, and provides computational facilities for simulations.

At the second highest level are the major subsystem controllers, including the controllers for the plasma state, the plasma diagnostics, the data handling system, and the plant system. The function of these controllers is to execute requests for subsystem responses made by the central processor. For example the plasma state controller creates a preselected plasma, contains it over the plateau regime, and shuts it down along a benign trajectory. Similarly, the diagnostic controller operates the diagnostic devices, makes the calculations required to convert raw measurements to plasma state variable values, and transfers the measurements to the data handling controller and to the central processor where they may be compared to preselected state values and used in closed loop control of the plasma state.

At the third control level are the controllers of the various specific devices. These may be either hard-wired program computers or sequencers whose function it is to coordinate the device-specific controls required to obtain a given output. For example, it may be required to set the light intensity output by the lasers according to plasma density and to make corresponding adjustments to the detector sensitivity or amplifier gain.

An important part of the system design effort will be directed toward the problem of allocating control of detailed processes to the controllers at each of the three levels.

Problems of assigning specific control operations to the various subsystems depicted in Figure 1 are discussed below. The discussion is divided according to the four major divisions of the system shown in the figure. Although the discussions are specific to the sample system organization, they nevertheless reflect control problems associated with the major subsystems contained in most experimental fusion devices.

3.1 Plasma State Controller

The function of this controller is to achieve and maintain selected plasma state variable trajectories. Investigations related to this controller will be centered about the following two questions:

1. Which plasma state variables should be controlled in open or closed loop modes?
2. To what degree can these controls be effected?

In tokamaks the major plasma radius is a candidate for closed-loop control, while the plasma current may possibly be controlled open loop (as is presently done in some machines). Other candidates for active control include plasma density, temperature, rotation, heating rates, potential, etc. Each state variable will be examined with respect to the possibility and desirability of its active control.

Since answers to questions 1. and 2. above are machine dependent, numerous options will exist for sizing this controller. Given answers to these questions for specific machines, several alternate formations of this controller can be devised. The scaling will depend upon details such as which variables are to be controlled, and whether the control is open or closed loop. The complexity and time delays related to pertinent diagnostics, as well as the amount of computation to be carried out, will also affect the plasma state controller. In this connection answers to the following questions will be sought:

1. What calculations can be made concerning the relationships between plasma state variables during the plasma "plateau" period?

2. What calculations can be made during the start-up and shut-down regimes related to the dynamics of these regimes?
3. What calculations can be made between operational cycles? (There may be two orders of magnitude more time available between operational cycles than during operation).
4. What are the advantages of analog vs. digital calculation and control?
5. How much time is involved in transforming each raw diagnostic measurement into a useful state variable value.
6. Are measurement statistics important to the problem?
7. Will feedback ever be required from the plasma state controller to the diagnostic devices in the sense that the diagnostic operational regime is altered?

Heating and constraining of the plasma is accomplished by a group of separately operated subsystems including magnets, plasma heating devices and divertors. This section is concerned with the control problems originating within these subsystems. Instructions from a central plasma state controller to the subsystems calling for a particular output may require several controlling adjustments within the subsystem. These adjustments must be harmonized as well as controlled separately to insure proper function of the subsystem, and to insure that the desired effect on the plasma state is achieved.

3.1.1. Plasma Heating

Many different heating techniques can be applied to tokamak type fusion devices. The major heating sources, however, are expected to remain the induced plasma current and energetic neutral beam injectors.

The plasma current not only contributes to plasma heating but also affects plasma stability, confinement, and column position. Control functions of the system in regard to the ohmic heating transformer will consist of calculating and commanding the appropriate current time profile consistent with experimenter requirements, power supply limitations, plasma position control capabilities, runaway electron considerations and toroidal field strength. Due to the large energy requirements, this control will probably be open-loop or open loop with trim. Because of the inter-relationships of confinement and heating it is not possible for the experimenter to select all plasma parameters independently with plasma current as the only heating source.

Neutral beam injectors interact with the plasma in a manner sufficiently different from the joule heating to allow another independent control on the plasma parameters. The proportion of energy transferred to the two plasma constituents, ions and electrons, depends on the plasma current, and injector voltage and current. Given the open loop current, drive profile and other plasma parameters, the ohmic heating may be estimated. The plasma state controller would control the number of injectors, the voltage and current of the various beams to arrive at the proper ratio of electron to ion heating to achieve the desired experimental conditions. For example, a series of experimental runs may be desired with the electron-ion collision frequency held constant, to aid in the investigation of scaling of diffusion coefficients. As the other plasma parameters (q , T_i , B_p) are varied to investigate diffusion scaling, the collision frequency [$f(T_e, n)$] may be held constant by controllable injector beams that allow independent control of voltage and current.

The control of a beam line encompasses many interacting units: The ion source, the extractor, the accelerator, the neutralizer, the transport section, the ion removal unit and the energy recovery unit.

Reconfiguration of the operating point of the injector will require open and closed loop control of the various pressures, voltages, focusing potentials, and magnetic fields so that the beam parameters may be altered quickly without danger of damage to the unit by the high energy beams. This beam line control will require numerous sensors on the system and perhaps a simulation of the unit in the processor system.

3.1.2 Confinement

Confining magnets in tokamaks and other experimental plasma devices can be categorized according to field strength and field variability. Three size ranges are evident.

A "large" category is represented by the toroidal field magnets in tokomaks and stellarators and by the main field coils in mirror machines. These magnets are likely to be cryogenic in coming generations of experimental fusion devices. The fields may possibly be adjusted between operating cycles; however, the time scale for such adjustments will depend upon power supply capacity. Control functions of the central processor with regard to these magnets will consist of bringing the magnets up to nominal field strength and making adjustments as directed by the experimenter. In concept the experimenter will set a field value at the control console, and the central processor will activate a data display unit showing the required charging or discharging interval, while at the same time directing the plasma state controller to carry out the desired alterations in the field. A potential area for feedback control involves the superconductivity problem. The voltage across the leads of the superconductivity coils is an indicator of the state of the magnet. A feedback system based upon adjustments in the coolant flow rate or pressure could be devised to counteract any developing non-superconductive regions within the magnet. Based upon the lead voltage the central processor may initiate a controlled discharge of the other toroidal field magnets to minimize the mechanical stresses.

In the second magnetic size category are current transformers in tokamaks and Ioffe-Bar conductors in mirror machines. The fields here are of intermediate size; magnets are not super-conducting, but are cooled to liquid nitrogen temperatures. The transformer coils in tokamaks perform a dual function of confinement and heating, and the control system must be cognizant of both applications. Currents in these conductors are likely to be controlled mostly open loop with a preset plasma state trajectory; however, feedback control could be used for fine adjustments.

The third category of magnets and field devices includes the relatively small field windings such as vertical field coils on tokamaks and stabilizing coils in theta pinch machines. These devices will be controlled with feedback over a wide range of field strengths. Time scales for the control of these fields depend upon the field interaction with wall material through image currents. On the subsystem level the control problem with these devices involves mainly current and coolant control.

3.1.3 Divertors and Limitors

The testing of divertor designs will be an important part of the next generation of fusion experiments. Preset adjustments in divertor fields will be made to study the effects of the cross-over point positioning. The divertor pumping system may operate with feedback control, changing rates as the particle flux changes. Magnetic limitors may be used to study plasma density distribution. Calculations relating the plasma density cross-section to the limiter current could be made by the central processor via the system simulator between operational cycles.

3.2 Data Handling Controller

This controller manages the many data handling problems related to the system. It interfaces with the display portions of the control console where it displays system readiness, plant malfunctions, simulation results, and experimental results. The display format will include cathode ray tracings, paper listings, and digital alphanumerics.

System function data, raw and transformed diagnostic data, and control settings will be taped by this controller.

The control problem for this device is generally one of scaling to meet system requirements, and designing to meet the system aim of maximizing operator control.

3.2.1 Control Console

As with the data handling controller, the problem here is primarily one of designing to support the system goal of maximum versatility. Problems of data display are discussed in the following section. The control console will interact with the central processor through the plasma state settings, and through test procedures that ensure that control settings have the proper effect on the system.

3.3 Plasma Diagnostic Controller

In order for the central processor to achieve its goals as a system supervisor it must be relieved of requirements to interface directly with the high-bandwidth data stream from the diagnostic instruments. In the control structure of Figure 2, the task of interfacing the diagnostic instruments to the central processor is relegated to the plasma diagnostics controller.

The control problem in diagnostic devices involves two areas; control of the elements of each device to insure proper function, and acquisition and processing of the specific measurements. The data passed on to the central processor will be of two types; high speed data that is sent continuously, even during a pulse, and slower speed data that may be sent only between shots. In the former category would fall measured parameters that are used by other system elements in closed loop control and diagnostic information that is pertinent to the malfunction detection and emergency shut-down system. Other data falls in the latter category.

The time response performance requirements differ greatly among the different diagnostic instruments. In all cases the diagnostic controller must be able to acquire data at a sufficiently high rate to avoid loss of information from the various sensors. In cases of open-loop measurements, this requirement is the main performance specification to be met. The performance requirements associated with sensors used in closed-loop control, e. g., magnetic probes used as plasma position sensors, are considerably expanded. The loop-closure time must be sufficiently small for control loop stability. For the system configuration shown in Figure 1, this time includes the data acquisition time in the diagnostic controller; the processing time for generating the parameter of interest, e. g., plasma position, from the input data and stored calibration data; and data transmission time from the diagnostic controller to the vertical field controller (plasma state controller).

The diagnostic controller must provide the capability of acquiring and storing experimental data from hundreds of channels of instrumentation

at rates that may reach several hundred kilohertz. One implementation that solves this problem is shown in figure 2. It is an extension of the system presently in use on ALCATOR. A high speed data buffer (an analog FM drum in ALACATOR) is used to relieve the controller of the high rate data stream. The buffer is used to acquire and store all the parameters to be measured during a machine pulse. A great proportion of these data are not needed by the system or its operators during the pulse. The hi-speed buffer stores the data for later processing and thus relieves the computer network of the large data transmission requirements that would otherwise be required.

The diagnostic controller is thus free, during a pulse, to acquire and process the smaller number of parameters that are used for safety monitoring and closed loop control. They are acquired through the multiplexer/converter, processed and sent to the central processor.

Between machine pulses the diagnostic controller will have two functions: (1) continuous parameter monitoring, and (2) data buffer unloading and measurement processing.

The structure of figure 2 is one method of meeting the performance requirements for the diagnostic controller. Different structures should be analyzed to determine the configuration that achieves sufficient response time, minimizes system complexity, and does not compromise regular data transmission paths.

Other design problems to be investigated deal with data retrieval, data storage and data for control room display. All data that is acquired, must be properly identified and stored in an easily retrievable format for reprocessing.

Data structures and formats must be designed to the diverse requirements of analyses, display, retrieval, storage, transmission, and compatibility with other data types existing in the machine that use common data talk and machine resources.

For immediate use of the experimental personnel, many reduction calculations will need to be made for display purposes. These will often require use of multiple sensor inputs to arrive at the desired plasma parameter. The diagnostics controller must be designed to provide not only the capability for performing many such calculations quickly but to allow rapid modification and additions to the programs by personnel in response to changing experimental requirements.

FIG. 2.

3.4 Plant System Controller

The plant system controller operates the various experimental support system including power supplies and coolant, vacuum, and fueling systems. Cooling system control involves primarily monitoring of liquid He and N₂ levels in storage tanks; however, if these coolants are produced on-site, then the problem is expanded to include control of the production machinery. For the vacuum system, it will be required to control pumping rates and vacuum levels, pressure gauges and leak detectors. Control of the fueling system would involve the same sensors; however, additional storage and pumping for H₂ would be used. Experiments on D-T burning would require a much more complex fueling system. Power supply control would involve generators and storage facilities, and the array of meters necessary to monitor the system state. The complexity of the power supply control problem would increase considerably if an energy recovery system were included.

4.0 Design of Interactive Devices

4.1 Data Display

Well conceived data display will be helpful in present engineering studies, but will be crucial in future interactive control of an actual large scale fusion experiment. Consider a tokamak executing its schedule of shots and recycle intervals. The operator needs to see what has happened in each shot and what can be expected in the next shot as a result of alternations he makes in the controls. The data has to be presented to him in a format easily assimilated so he can make judgments quickly.

In the context of display requirements, data can be thought of in several major categories. The first category comprises gross, lump parameters which can be presented as single numbers. Examples include plasma state variables, such as peak density, central electron and ion temperatures, and total plasma current; beam parameters such as energy per particle and total power; and currents in transformer and magnetic coils. The next category of data comprises functions of a single variable. Examples include time plots of controls (for instance, vertical field control current) and time histories and radial profiles of plasma parameters (for instance, horizontal and vertical position, current, temperatures and heating rates). Such material should be presented graphically, as variable versus time or radius.

These first two categories of data are the most common, and their display has already been the subject of much careful concern in the DAS-1800 system at Princeton. The features of their system have evolved in response to user experience, and can be regarded as good indication of what a data display system really needs. The general pattern of computer

use on DAS-1800 is: a) data acquisition using standard MPX analog input routines, b) data storage on disk also using MPX routines, and c) display of raw data or calculation results on Tektronix storage oscilloscopes ("memoscopes"), with hard copies of the displays available from associated Tektronix hard copy units. Displays are directed to one of sixteen scope channels in the experimental machine control rooms. Any channel can be monitored from the computer room. The basic display subroutines erase any channel, draw axes, write text, and plot data as a connected line or as a series of points, asterisks, etc. All subroutines are easily callable from FORTRAN programs. Messages and numerical values can be written on the displays using FORTRAN write and format statements. Memoscope displays are easily programmed, and hard copies from the associated units are quite legible. The usefulness of all these features is illustrated in application to seven major experimental measurements at Princeton: thermal conductivity, ATC plasma position, ion temperature, magnetic properties of instabilities, ST x-ray spectra, Thomson scattering, and heavy ion beam momentum spectra.

It is possible to identify the categories of data for which the technology of presentation is not yet so well developed. Some relevant data is a function of two variables. A good example is shape of the separator in divertor experiments, shown on a two dimensional representation of plasma cross section. Finally there is a category of data that is three dimensional in nature because it has to do with failures in the nominal axisymmetry of the tokamak. Examples include locations of dangerous proximity of plasma and wall, locations of concentrations in particle flux on the wall, information on wanderings of the divertor separatrix, and characterizations of significant plasma instabilities. The presentation of such information poses a real challenge. Some of it might be presented in words: for instance "quadrant threetop." But some might be better presented pictorially. Suitable representations will be considered in proposed studies.

4.2 The Tokamak Simulator

Efforts to design and implement control strategies for the next generation of fusion devices will require simulation capabilities. Simulation is needed both for the engineer engaged in analysis and development of control strategies, and later for an operator applying interactive control in an actual experiment. The capability required, say for a tokamak, is simulation of the plasma and all the associated devices that accomplish fueling, heating, confinement, positioning, and wall protection (e.g., injection beams and current loops).

The engineer engaged in analysis and development of control strategies needs such a simulator to help anticipate various supervision, control and data processing requirements. In detail, the simulator will provide rapid exploration of relevant operating regimes, so that a nominal sequence of events can be selected. The time scales encountered can be used to identify what parts of the sequence need to be preprogrammed and what can be subject to active control, what parts must be automatic, and what can accept operator intervention. Thus the basic supervisory structure will be defined. Then the simulator should be able to predict the consequences of deviations from nominal conditions in the experimental device (e.g., perturbations of individual magnetic-field-producing current loops or individual injection beams, etc.) so that the importance of these can be assessed. Requirements for control will thus be identified. Then the simulator should predict the responses of available diagnostic devices to plasma parameters, so that procedures

for interpretation can be devised and tested, and so that needs for different diagnostics can be identified. Data flow rates can be estimated so that computation requirements for real-time processing can be quantified. Various overall control systems including sensors, processors and effectors will be proposed, differing perhaps in functional division between control processor, local processors, sensor preprocessors, and so on. The simulator will predict the consequences of the various strategies, so that optimum procedures can be selected.

The operator applying interactive control in an actual experiment requires the simulator for a different and more restricted set of uses. The tokamak is presumed to run in a sequence of discrete shots and recycle intervals, and the simulator has a role to play in both modes. It precalculates and stores much necessary information enabling the control system to function during a shot, when it has to accept as input actual diagnostic measurements corrupted with noise, interpret those measurements to recognize what if anything is different from nominal; and produce as output the actual signals to initiate correct controls. Between shots, the simulator is needed to help structure the next shot. Typically, the operator might be trying to modify controls from one shot to the next in order to approach some nominal situation. The first thing the operator needs between shots is some rough interpretation of the data generated in the previous shot. On the basis of this, he might propose alterations in various controls. But before implementing these in the real experiment, he would test them out by letting the simulator

predict the consequences. If the predictions are accurate, the procedure serves to guide the experiment to the desired end, but even if the predictions are inaccurate, then errors in underlying assumptions are corrected, which when connected, lead to improved predictions in following shots.

The great variety of uses for the simulator implies need for a great deal of flexibility. It is possible to think of the simulator as performing three major functions, and to identify the flexibility required in each. Those major functions are acceptance of input parameters, computational modeling of physical processes, and presentation of output. It is clear that the simulator's first requirement is to accept inputs that represent a tremendous variety of engineering questions. To this end, the simulator should be compartmentalized. The plasma and each of the associated devices should be separable from the rest as subroutines. This approach will be particularly useful in iterative control design, trouble shooting, and fault isolation. The simulator should also have input capabilities that will assist the design of the control console for use in a real experiment. For this purpose, the simulator could be connected directly to prototype versions of the console. The next simulator requirement is for run time tailored to the application. At least three time scales can be identified, one for day to day engineering use with reasonable turn around, one much faster for real-time interactive control use, and one perhaps slower for providing accurate benchmark results to support important conclusions. Most of the simulator run time will be consumed in computational modeling of physical processes; hence, several versions of every physical model will be required. It should

be made easy to plug in whatever version has the appropriate time scale for the particular application. The compartmentalized, plug-in conception of simulator and physical model serves yet another requirement: it should be easy to update the simulator on the basis of empirical information. The final simulator requirement is for flexibility in output format. For engineering purposes, various kinds of hard copy and video console output capabilities will be useful. Much of the output should be graphical or pictorial rather than numerical. Efforts to provide the most useful output formats for the simulator will contribute directly to the eventual design of the data display system for use in real experiment.

5.0 Reliability Considerations

The following sections deal with system performance with respect to achieving minimum outage time. This aspect becomes potentially more significant since the integrated control system is, in principle, vulnerable to common mode or single point failures which if not carefully anticipated, could lead to excessive and serious outages. It is the belief that reliability features, if considered during the preliminary design stage, can be incorporated into the basic design and mitigate this class of faults. For this reason it is discussed herein and related to other system design considerations.

5.1 Reliability and Quality Assurance

Control System design and subsequent hardware implementation must adhere to the highest available standards of reliability. These are above the level of best commercial practice and in some cases approach the levels currently found in aircraft and spacecraft.

Reliability must first be sought in the system architecture, with provision for suitable redundancy, in areas where failures are expected and where they will be significant. Of particular concern will be the central processor and other device essential subsystems, and the sensors. To the extent that the sensors are shared between the control system and experiments, their reliability will be important; some level of sensor redundancy is probably indicated.

Control system and experiment reliability are generally achieved by applying some general principles, including, but not limited to, the following*.

1. Design simply to minimize the complexity of the control equipment.
2. Partition hardware functions where

* The design principles outlined were used successfully in a high statistics synchrotron experiment (Ref.'s 2 and 3).

possible, so that single hardware failures affect only one subsystem.

3. Use stringent design standards and redundancy for common functions or equipment (e. g., processor).
4. For corroboration of data and validation of control signals, employ functional redundancy with diversity in architecture or equipment, or both. Incorporate and exploit failure tolerance features where possible.
5. Employ extensive diagnostics to assure proper machine operations and prompt recognition and isolation of failures, including end to end checks under computer controls.

In addition, other useful measures may include:

- Using standard instrumentation (e. g., CAMAC or equivalent) for replicated functions in logic, signal processing, transmission, processing and display.
- Avoid homemade "one of a kind" circuits except where necessary.
- Anticipate and design around disturbing environmental influences, such as EMI/RFI induced transients and thermal variations.
- Use of control room shielding, adequate cooling, radiational shielding, shielded cables and well design bulkheads for cable patching.

Good design for reliability will normally be preceded by predictive analysis of failure rates. Except where the rates are known or failure history is available, mathematical models or limited testing would be required. In order to avoid the limitations and rigidity of most a priori postulated mathematical models, analysis and testing should proceed in accordance with general theory, such as that discussed in Reference 1. With this approach, as experimental and operating time is accumulated, predictions can be updated, leading to possible modifications of equipment.

- Ref. 1: C. K. Whitney, "Analyzing Reliability Data and Designing Acceptance Tests," IEEE Trans on Reliability, May 1966
- Ref. 2: Binnie, Wilson, Nicholson, et al, "A2 Production in the Channel $\pi^+\pi^-\pi^-$ Near Threshold; Phys. Letters 36B (1971), 257
- Ref. 3: Binnie, et al, "Study of Narrow Mesons Near Threshold," Phys. Rev., Vol. 8, #9, 1 Nov. 1973

5.2 Failure Detection

Failures in the large scale fusion control system described in this report can occur in several degrees of severity. The most severe are catastrophic, causing termination of machine operations. Less severe are partial failures affecting experiment quality, but not terminating operations. The severity of any failure will be determined in part by the importance of the control system function affected, and in part by the availability of functional and equipment redundancy. The job of failure detection is to isolate the failure so that its severity can be assessed and the least disruptive course of action can be taken.

As an example, consider the plasma diagnostics controller. Single unit sensor failures in that subsystem, except for the controller itself, are probably not catastrophic and could be repaired on-line if necessary. By contrast, failures in the plasma state controller, central controller, and selected portions of the plant system monitor (e.g., Power Supplies) will normally shut the machine down. Some equipment redundancy, whereby standby units can be connected in quickly (manually, remotely, or automatically) is undoubtedly required. A lower level of failure isolation may be required if on the spot repairs are required at the circuit board level. In general, such repairs will be carried on off-line utilizing appropriate special test equipment. Consequently, standby units are postulated. The nature of the failure detection scheme and resultant switchover to redundant units needs to be developed on a flexible basis, tailored to the needs and peculiarities of the subsystems.

As a starting premise, provisions for prompt switchover between power supplies^{*} should be anticipated. Similarly the need for standby central processor can be anticipated. Current practice utilizes a single

* Generally, not automatic for high current magnet supplies.

active processor, with data and status recording being done by the standby, which also contains the main program. Alternative techniques based on a single processor utilize a backing store (disk) for program storage and a tape deck for storage of data. The control processor can then be restarted manually from paper tape bootstraps or remotely from the central controller. The single control processor can scan data on-line prior to storage and store histograms for periodic on-demand CRT display or hard copy teletype readout. This scheme may be appropriate for subsystem controller while the full redundant processor described above may be superior for the central processor.

Failure detection can be effected very well with these elementary redundancy and data analysis and display provisions.

The following features might typically be included:

I. Sensor Failures (Plasma Diagnostics)

- Same Sensors/Data
- Individual Sensors

- Same Sensors/
Different Data

II. Subsystem Controller Failures

III. Data Transmission and Cabling Faults

Redundant and Identical Sensor
Comparisons by Diagnostics
and/or Central Control. Operator
Inspects Histograms

- Int. Data Rate vs. Time
compared to reference
sensors (computer derived)
- Power Supply Trip - Direct
Logic Level Indicator
- On-line disconnect
- Tests of Particle, Detectors
with artificial light sources,
electrically stimulated between
shots, results automatically
recorded, displayed
- Compare Integ. Data Rate
Ratios between sensors
- Pilot Signal Insertion via
sensor or alternate input
channels between shots under
central processor control.
Comparison with predetermined
response,
- Normal internal controller
checks including check sums,
test routines, etc. Redundancy
coding, including parity for
data transmission errors,
- Parity/coding checks on data
- Pulse height monitoring of
particle detectors at remote
end

IV. Plant System

- Coolant System
- Vacuum System
- Fueling

VI. Data Handling

- Controller
- Control Console
- Display
- Data Storage

- Provision of Redundant Cabling, periodic swapping and comparisons
- End to end checks using sensor or injection of pilot signals
- Pump Speed Monitor (trip input)
- Monitor ΔT Power via redundant RI sensors (inputs to trip system) or equivalent
- Monitor Vacuum via redundant vacuum gauges (trip input)
- Continuous level monitors
- see above
- Testing end to end checks
- Push to Test Fault Lights
- Periodic Panel Lamp Tests
- Integrated Button/Light Switch
- Periodic CRT Test w/test Tone, maintaining trigger and stored test pattern, data fields
- Checks on data errors prior to tape or disk store
- Off-line internal checks on data and compare with on-line
- Equipment checks on working and backing stores

5.3 Redundancy Management

Given the need for redundant functions and equipment, to compensate for inevitable faults and failures that will occur, options exist regarding employment of redundant elements. These may be considered in several classes.

I. Built in Active Redundancy - on-line

Refers to employment of multiple elements operating on-line, anyone of which is adequate for the function. Examples are multiple sensors. Management is minimal and consists of selecting the good channels of data either by comparisons or by voting, either on-line or during off-line data reduction.

II. Active Standby Redundancy

Certain elements may be sufficiently crucial to control system operation that use of an active standby unit may be justified, such that failure of the primary unit will cause the standby unit to be activated for the primary role. Examples may include the central processor or display consoles where the likelihood of failure is relatively high but the function is too important to permit a function failure. Failure without standby would constitute an outage for the system.

The management consideration in this instance deals with automatic switchover, using built in diagnostics and switching, versus manual or semi-automatic, via operator action. Some degree of automatic switchover is anticipated and would likely be employed in central processor and other vital logic functions.

Failure detection of the display/control unit is probably by operator, who may then activate standby units manually or anticipate dropouts by employing CRT's in parallel.

III. Passive Standby Redundancy (Spares)

For units for which failures are anticipated spare modules are kept in the area. Upon diagnosis of failure of any unit, it is removed and identical spare put in its place. This is referred to as a remove and replace approach. Failed units are repaired off-line in a shop with special diagnostic equipment. Failure isolation is then required down to the replaceable unit level; these failure indications are frequently built in, but removal/replacement is manual.

Without fault isolation to the lowest replaceable unit, entire spare racks are required in standby. These spares may be in place (e.g., power supplies) but will need to be connected to the load previously driven by the faulty unit, and then switched on. Switchover is normally manual and effected in a short time. In many common trips, the fault resides in a fuse or circuit breaker, which can be readily fixed or replaced within 15 min. In most instances magnet power supplies and like supplies are collocated so that a single variable supply can service any one of the magnets in a certain current range.

Passive standby redundancy is clearly limited to units outside the reactor core area, and will normally encompass supplies, control-control room electronics, and other logic. All other units must be remotely switched either manually or automatically.

IV. Spares

A buffer stock of spares of replicated units is maintained for the reactor and topped up periodically from the recycled equipment.

Standardization of reactor and experimental electronics (e.g., CAMAC) creates a central pool of spares from which experimenters can draw.

6.0 Scram Systems

The failure detection system will automatically display any failures to the machine operator. If the failure is a critical one in a system for which there is no backup, it may automatically activate one or more scram systems. The scram systems may also be activated manually by the machine operator.

These unscheduled shutdowns can range from relatively minor ones to severe emergencies. An example of a less severe shutdown would be aborting a shot because of excess hard x-rays from runaway electrons. An example of a more severe emergency would be the quenching of one of the main superconducting magnets.

Several of the subsystems may have their own scram systems. There will also be an overall scram system for the device as a whole. The scram system will have to be designed to satisfy a number of partly conflicting requirements; for example, data protection, vacuum protection, device protection, operator protection, maintenance of superconductivity, and energy conservation. The scram systems may use active feedback to follow desirable abort trajectories and may involve special techniques to rapidly and safely dump large quantities of energy from the system.

It is evident that scram requirements will affect the basic design of the device in many ways. Because the scram controller will have a major impact on the scram system design, this is one area in which the control system will have a large effect on the design of the device as a whole. Effective use of modern control technology is required to implement the device scram system.

7.0 Task Outline

The proposed areas of investigation fall into the three broad categories of general control system studies, simulation construction, and investigations of specific control problems in cooperation with other laboratories. Work items within these categories are listed in Table I, with references to appropriate report sections or appendices where items are discussed.

Table I
Task Outline

		<u>Text References</u>
I.	System Studies	Sections 2 & 3
	1.1 System Design	"
	1.2 System Structuring	"
	1.3 Functional Allocations	"
	1.4 Definition of Modular Elements	"
	1.5 Scaling Problems	"
	1.6 Subsystem Structuring	"
	1.7 Interfaces	"
II.	Simulation Studies	
	II.1 TOKAMAK	Sect. 4.2 App. A1
	II.2 Neutral Beam - Plasma Interactions	App. A2.2
	II.3 Display and Control Device Issues	Sect. 4.1
III.	Center Support	
	ORNL Support	App. A.2
	PPPL	App. A.3
	U. of Wisconsin	App. A.4
	Other Centers	

APPENDICES

A.1 Modeling Problems

This sect. concerns projected requirements for computer simulation capabilities in the Draper Laboratory controlled thermonuclear fusion research effort. A distinction is made between simulation and modeling. Simulation denotes a system concept, involving in part some basic computer modeling of physical processes, and in addition facilities for input and output of model parameters in a form suited to the intended applications of the overall simulation. Generally, the modeling provides the quantitative information necessary 1) to provide interpretation of the limited diagnostic measurements that can be made in the hostile environment of a fusion reactor and 2) to predict the consequences of various control strategies that are feasible. But the importance of the system concept of simulation becomes clear when we consider the intended applications of these functions. Initially, the simulations will support analysis and development of control strategies. However, in the future, they will support control of actual experiments. Each of these two modes of application imposes unique requirements, as discussed below.

When applied to the analysis and development of control strategies, the simulation has to be sufficiently general to adapt to a reasonable variety of particular problems. Further, it has to provide results in an easily interpretable format (graphical or pictorial, for instance). Finally, the simulation as a whole has to run fast enough to provide reasonable turnaround for the engineer. The following example illustrates the requirements: Suppose there is proposed a strategy for plasma position control that involves manipulation of the currents that generate the plasma confining magnetic fields. The ideal simulator might accept as input a vector function of position to represent the nominal spatial distribution of explicitly applied currents. It should accept inputs that are quite arbitrary, in order that the simulation not be machine specific. A desirable form of output would be a computer plot on a CRT display, showing a plasma-containing surface with magnetic lines of force. Also, one would want estimates of the measurements expected from any sensors proposed to monitor these fields. The simulator should allow observation of the changes in this plasma picture and the accompanying measurements as the amplitude of some control currents are altered differentially. All of these system requirements are in addition to the simple modeling requirement; namely, that the software should calculate accurately the

fields due to all explicitly applied currents, plus induced plasma currents and image currents in metallic walls, lithium blankets, etc., and predict accurately the sensor responses. All of the requirements contribute to a truly useful engineering tool. To meet them all, one requires a complex system, probably involving both digital and analog computing, a sophisticated pictorial display, as well as a computational model of the physical processes that is sufficiently fast for the purpose.

Now consider the application of simulation to the control of an actual experiment. The same example of current manipulation poses quite different simulation requirements. First, the fusion processes are entirely too fast for the human being to be part of the control loop. The graphics which were so useful before are no longer of prime importance. The outputs of the simulator will include signals to govern control currents directly. Furthermore, the inputs to the simulator are no longer limited to those provided by a human. They now include the measurements from the sensors, corrupted with noise. From these, the model has to estimate the existing pattern of magnetic fields. Then it has to find the control increment that will bring the fields to some nominal situation. Both of these model functions are the inverses of the functions performed by the model when applied as an engineering tool. Consequently, it is likely that an essentially different model would be required. Furthermore, control of an actual experiment imposes new and more stringent speed requirements. This means either a very fast computer code or else very fast reference to a catalog of results accumulated from a longer running code. These stored results might just comprise partial derivatives for use in a simple linearized model of small excursions from a given situation. The point here is that although the physical phenomena modeled are the same in both applications, the model itself and the overall simulation are quite different.

Limiting attention for the moment just to measurement and control of plasma parameters, it is already clear that while some of the relevant physical phenomena are straightforward, some are probably difficult even to model adequately. Some examples of the processes that are nontrivial to model include the following:

- Magnetic loop currents as a function of plasma position;
- Rogowski loop signal as a function of toroidal current;
- Neutron flux as a function of burn rate, density and temperature, especially with spatial distribution of these parameters;
- Sputtering rates and heat loads as a function of particle flux;
- Intensity of line radiation as a function of impurity spatial distribution;
- Thompson scattering as a function of temperature profile;
- Plasma current distribution as a function of magnetic history.

The list of difficult modeling problems is long, but it is expected that many of them have already been treated to some extent elsewhere. It will be necessary to survey carefully the modeling and simulation capabilities already existing in the laboratories with which we collaborate. Where there exist models or simulations that would be practical for us to borrow, it will be necessary to gain actual experience using them. In determining the practicality of such borrowing, the kinds of questions to ask include the following:

- What order of computation time is required by the basic model and by any input-output facilities that are used with it?
- If the model itself is time consuming, what level of realism does it represent and what simplifications would least affect its accuracy?
- Do the input output facilities suit our needs?
- If not, what would be involved in creating a system that would so suit us?

For our purposes, there are likely to be many cases in which we wish to de-emphasize the detail of models and accentuate the sophistication of input-output facilities. The kinds of things we can do to achieve such a rebalancing include the following:

- Use of lumped parameters to replace distributed quantities;
- Separation of phenomena occurring on vastly different time scales and proper choice of time steps for numerical integration;

- Approximation of nonlinear equations with truncated power series, and simple representation of feedback loops with nonlinear elements;
- Use of coarse angular discretization and other radiative transfer modeling techniques in describing velocity space for the modeling of scattering processes.

APPENDIX A2.1
Plasma Position Control

The Charles Stark Draper Laboratory, Inc.

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MEMORANDUM

TO: CTR Distribution
FROM: R. V. Ramnath
DATE: 9 May 1974
SUBJECT: Vertical Field and Plasma Position in the Tokamak

Abstract

The time-dependent plasma position in the horizontal plane of a tokamak is usually determined using linearized equilibrium plasma theory, including plasma equilibrium inside a conducting shell as well as time-varying gap effects. The vertical field has to be computed by solving a parabolic partial differential equation, with boundary conditions depending on a small parameter. While zeroth order theory is currently employed in computing the plasma position in ORMAK, this memo suggests improvement in accuracy to be obtained by developing a higher order theory. If the first (or second) order result is nonuniform, the method of generalized multiple scales could provide a uniform solution of greater accuracy.

The horizontal position of the toroidal plasma is a rather important variable to be determined. This information is required for several purposes, such as for feedback control and to interpret data from various diagnostics. The time-varying plasma position is usually determined from a knowledge of [1, 2]:

- (1) B_θ (inside and outside the plasma)
- (2) I (plasma current)
- (3) B_z (the applied vertical field).

From the linearized equilibrium plasma theory of Mukhovatov and Shafranov [1], the shift Δ of the plasma center from the minor axis can be determined in the form:

$$\Delta = \frac{b^2}{2R} \left[\ln \frac{b}{a} + \left(\Lambda + \frac{1}{2} \right) \left(1 - \frac{a^2}{b^2} \right) \right] - \frac{cb^2}{2I} B_{\perp} \quad (1)$$

with the usual notation [2, 3].

All the quantities in (1) can be measured except $B_{\perp}$ which has to be calculated. $B_{\perp}$ can be determined by solving a diffusion equation

$$\gamma_{xx} + \frac{1}{b} \gamma_x - \frac{\gamma}{b^2} = \frac{4t\sigma}{c^2} \gamma_t \quad (2)$$

with the boundary conditions

$$\begin{aligned} \left(\gamma_x - \epsilon \frac{\gamma}{b} \right)_{x=0} &= K_1(t) \\ \left(\gamma_x + \frac{\gamma}{b} \right)_{x=b} &= K_2(t) \end{aligned} \quad (3)$$

where:

$$\begin{aligned} \gamma &= r B_{\perp} \\ \delta &= \text{shell thickness} \\ \sigma &= \text{conductivity of shell} \\ b &= \text{shell radius} \\ R &= \text{major radius} \\ \epsilon &= \frac{b-d}{b+d} \ll 1 \end{aligned}$$

K_1 and K_2 are as given in [3]. The equations (2), (3) can be transformed into [3]:

$$\gamma'_{yy} + \gamma'_y - \gamma' = \gamma'_\tau \quad (a)$$

where

$$\begin{aligned} \gamma' &= \frac{\gamma}{b} \\ y &= \frac{x}{b} \end{aligned}$$

with boundary conditions

$$\gamma'_y - \epsilon \gamma' = K'_1(\tau) \text{ at } y = 0 \quad (b) \quad (4)$$

$$\gamma'_y + \gamma' = K'_2(\tau) \text{ at } y = \delta' \quad (c)$$

$$\text{and } \gamma'(y, 0) = \gamma_0(by)/b \quad (d)$$

Hu [3] obtains the zeroth order (in ϵ) solution of (4) in the form:

$$\gamma'(y, \tau, \epsilon) = \exp\left(-\frac{y}{2} - \frac{5}{4}\tau\right) f(y, \tau, \epsilon) \quad (5)$$

where f is determined in terms of exponential, sinusoidal and complementary error functions.

It seems that a more accurate value of $B_\perp$ (i.e., γ') can be obtained by considering higher order terms in ϵ . The results obtained by Hu are appropriate only in the limit $\epsilon \rightarrow 0$. However, $\epsilon = \frac{b-d}{b+d}$ is not vanishingly small although it is less than 1. Therefore, it seems that higher order corrections are necessary to get an adequate accuracy.

It seems appropriate to suggest the following approach in order to obtain a more accurate and uniformly valid expression for the vertical field $B_\perp$ and then for the plasma position in the tokamak.

1. Develop higher order terms for γ' (to order ϵ and ϵ^2).
2. Study nonuniformities, if any.
3. If nonuniform then obtain uniform solutions using techniques such as: multiple scales, etc.

As the governing equation is parabolic and the problems seem to be of secular perturbation type, it seems that multiple scales method is more appropriate than employing either matched asymptotic expansions or Lighthill's stretching. The problem certainly has multiple time scales in the solution. Further, nonlinear scales [4] could lead to larger domain of validity. Another advantage is that the solutions could be obtained in terms of elementary functions instead of higher transcendental quantities such as error functions. This could lead to qualitative insight as well as computational simplification.

References

1. Mukhovatov, V. S., Shafranov, V. D., Nucl. Fusion 11, 605 (1971).
2. Colchin, R. J., ORMAK-TM-103, ORNL, April 25, 1973.
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A.2.2 Beam-Line Control

As described in the section on Plasma heating, the control of an energetic neutral particle injector beam-line is desirable for experimental flexibility, and for efficient use of the experimental facilities.

It is proposed to engage in two areas of effort on the controllable beam-line problem: (1) modeling and simulation of the system elements for development of feasible control schemes and (2) implementation of a selected control scheme on actual hardware. Both of these tasks require support of ORNL personnel for model development, verification of modeling results, as well as during implementation and testing of the control concepts. It is proposed to develop the control schemes on injector configurations that will be relevant to the next generation of fusion devices. Thus, the prototype would be able to provide actual support for research as well as make possible testing of the device in the actual environment.

A.3 ATC Instability Control

Low Frequency Feedback Control Experiment

Most instabilities in tokamaks manifest themselves as relatively low order helical perturbations of the basic equilibrium. An $m = 2$, $n = 1$ perturbation rotating at approximately 10 khz, observed in ATC and typical of observations in similar devices, have been shown to be sensitive to feedback control. The preliminary experimental results are sketchy -- linear feedback control with matched spatial mode numbers will change the frequency of the observed oscillation, and will entrap the oscillation at zero frequency (i.e., with a steady state $m = 2$, $n = 1$ magnetic perturbation). It is not known whether the zero frequency perturbation reduces the amplitude of the instability or simply makes it undetectable by the magnetic probes used at this time. A spatially nonresonant feedback field ($m = 2$, $n = 0$) has no effect on the rotating perturbation, nor is it capable of locking it into zero frequency status. It has not been possible to reduce the amplitude of non-zero frequency oscillation appreciably using the feedback amplifiers currently available. However, it is quite clear that interesting and possibly very important interactions with the perturbation are taking place and the ATC group plans a study of this phenomenon extending over the next several months.

There are many uncertainties remaining. The theory of radially localized modes is not well enough developed to predict with certainty the effect of feedback. Even more troubling, there are reasons to suppose that some internal perturbations produce no external magnetic signal at all. The effect of the instability on important plasma parameters is not known, so it is difficult to decide what level of fluctuation suppression will be adequate. There is a related question in the choice of either high sensitivity gain feedback systems used with moderate power amplifiers or with a moderate gain and sensitivity feedback system used in conjunction with high power amplifiers. Much will depend on the detector sensitivity and instability growth rate.

A.4 University of Wisconsin Support

The control system for a fusion power reactor may be expected to differ from the control system for an experimental fusion device. It would be very interesting to examine these differences by considering the preliminary control system design for a study such as UWMAK. A control system study for UWMAK would serve a number of useful purposes. First of all it would show what impact the control system would have on the basic design, operation, safety, and cost of UWMAK. Second it would provide a preliminary design for a power reactor control system. This preliminary design would identify key problem areas and could be used to help guide future research and development. Thirdly it would help identify the common elements of reactor and experiment control systems. Where these common elements exist, the experience with experiment control systems could contribute towards the ultimate development of reactor control systems. It might even be desirable to do some control system experiments on the experimental devices to prove out concepts that might be used on a reactor control system.

We propose to do a preliminary control system design for UWMAK. This design would be based on the latest available UWMAK data and expected operating modes. It might be necessary to make alternate designs for pulsed or continuous operation or for other uncertainties in either UWMAK or the control system. The work would be done in cooperation with the University of Wisconsin so that an effective integration of design efforts would result. The work would assume a state of the art in computer hardware, computer software, and other control system elements consistent with the UWMAK operational time frame.

APPENDIX A5
Control Catalog

1.0 CONTROL SYSTEMS FOR FUSION DEVICES

1.1 Introduction

Experimental fusion devices operating presently and proposed for the future are extremely complex systems composed of numerous complex subsystems. A compendium of subsystems for any experimental fusion device includes most or all of the following: power supplies and energy recovery system, magnet system, diagnostic devices, plasma heating devices, vacuum and coolant systems, and data processing equipment. The operational mode of these machines involves a temperature range of a hundred million degrees, and energy transfers during a working cycle of 10^9 joule.

If these systems are to be optimized in the broadest sense they must have a control system of matching sophistication. The general aims of such a control system should be to

- 1) maximize experimental flexibility,
- 2) maximize operator control,
- 3) minimize down-time.

By maximizing experimental flexibility, the maximum scientific return from each device can be assured. The plasma behavior is

27. determined by the magnitude and time variations of several
21 externally controlled parameters. These parameters involve
29 many subsystems either singly or in combination. Only the
30 orderly and comprehensive control of these subsystems can
31 permit a maximum of operator originated plasma state
32 variations.

33
34 Several levels of control functions are evident when the
35 hierarchy of systems in a fusion device are considered. (The
36 division of control operations according to "levels" is purely
37 functional and not meant to indicate a physical or electrical
38 separation of control operations.) A possible organization of
39 the system is shown in Figure 1-1. The first level of the
40 system is a grand system state monitoring device that matches
41 the states of all subsystems against a set of model values that
42 are partly pre-established and partly operator controlled.
43 Simple plant state assignments like coolant levels in
44 reservoirs would be preset, while plasma state variables would
45 be chosen at the start of each operational cycle. The central
46 processor would control abort, start-up, and shut-down
47 operations as well as the steady state operations.

48
49 At the next control level are the controllers for the
50 various subsystems. Subsystem controllers respond to the
51 central control request for a change of state by making all the
52 necessary adjustments in the subsystem. Included in this level
53 of subsystem controllers are the physical plant controller, the

plasma state diagnostic equipment controller, the data input and output controller, and the plasma state adjusting subsystem controller.

At the bottom of the control hierarchy lie actual control elements like switches, voltage controls, pumps, etc.

The above is but one example of a number of possible organizations of the control system for a large experimental fusion device. Each potential scheme for organization must be evaluated within the framework of the broader control issues mentioned earlier.

1.2 Aims of Control Catalog

The control catalog is aimed at providing a structure for the complete listing of the control problems associated with a large experimental fusion device. The catalog format allows for detailed listing of both theoretical control problems involving relationships among plasma state variables, and practical control problems related to the operational modes of the various subsystems. Thus, the listing begins with broader control issues, and sifts downward toward mechanistic details concerning the operation of switches. A pedagogic aim of the catalog is to acquaint both the reader and the authors with the broad spectrum of control issues associated with large scale experimental fusion devices.

1.3 Catalog Organization

The control catalog is organized around the plasma state. Section 2 discusses plasma state control issues, i.e., the relationships among plasma state variables, and the desirability and possibility of control of each variable. Section 3 discusses the control of subsystems which can alter the plasma state--for example the magnet system current control. Section 4 is concerned with control of the plasma state diagnostic devices. Section 5 discusses the data handling system and the transfer of plasma state information from diagnostics to the central processor, the control console, the experimental recording center, etc. In Section 6 general plant support system control is presented.

2.0 PLASMA STATE CONTROL

This section is concerned with the desirability for control and the controllability of the many plasma state variables. The two central questions to be addressed are:

- 1) Which plasma state variables should be controlled in open or closed loop modes?
- 2) To what degree can these controls be effected?

In tokamaks the plasma positioning and column position

instabilities are a candidate for closed-loop control while the plasma current may be possibly controlled open loop as is presently done in some machines. Other candidates for control include plasma density, temperature, rotation, heating rates, potential etc. Each state variable should be examined with respect to the potential and desirability of its control. The first part of this section is concerned with identifying the actively controllable plasma state variables. Each of the major variables is analysed in turn. This is followed by a discussion of the theoretical problems associated with control of the state variables. Examples of plasma state control for some specific fusion devices are given next, and the section concludes with a discussion of problems of modeling and simulation for control studies.

2.1 Transient Regimes

We use the term transient regimes to refer to the start-up and shut-down intervals. Shut-down operations include both normal and "scram" modes. Distinctive control problems arise in relation to each of these transient modes.

2.1.1 Start-up

The start-up mode involves various levels of operations including experimental facility start-up, fusion device start-up and plasma initiation. Facility start-up includes

controlling initial operations of the vacuum and coolant
subsystems, testing the operational status of diagnostic
devices and plasma heaters, and checking the data processing
equipment with developed status check codes. After checkout of
the central processor, the processor would monitor start-up
operations of the other subsystems. A second level of start-up
control involves the actual pre-experiment operations such as
magnet charging, heater and diagnostic device warmup, fueling
and vacuum pumping. These operations would be controlled by
the central processor also. Short time scale start-up,
involving the generation of a preselected plasma state is the
final start-up category. During this mode there will be a
controlled axial current buildup sequence, and controlled
external plasma heating. Feedback control may be desirable
during plasma build-up to alter a pre-planned trajectory if
unexpected state variable values are measured. For example
excessive hard x-ray intensity will be a measure of run-away
electron density, and excessive bremsstrahlung a measure of
unexpectedly high impurity levels.

2.1.2 Shut-down

At the end of a plasma cycle, when the axial current
transformer is turned off either because the power source is
exhausted or because of deliberate ending of the cycle, the
axial current is continued because of the changing flux through
the plasma ring. To avoid burning the walls or destroying the

limiter it is useful to control the shutdown by shifting the de-energizing mode (to bremsstrahlung or electron thermal diffusion) or using some technique to dump energy out of the plasma current and into storage. The hard x-ray level could be used here as a measure of the dissipative electron behavior, and the control could be the turn-off rate of the transformer current, or rate of cooling gas injection.

2.1.3 Emergency Shut-down

Shut-down situations resulting from a gross system failure such as electrical shorting, or coolant or vacuum system failures, may require a control structure that is distinct from the normal shut-down sequencing following an operational cycle. The emergency shut-down control sequence will be aimed at minimizing further degradation of the experimental device as a whole. Certain subsystems may be added to the device specifically for emergency shut-down, for example systems for failure detection and rapid dumping of stored energy. Issues related to emergency shut-down may influence the design of certain subsystems. For example toroidal magnets may be powered in parallel rather than in series. Feedback control may be required to achieve optimal shut-down rates in various flow processes.

2.2 Controlled State Variables--Steady State

2.2.1 Actively Controlled Variables with Feedback

2.2.1.1 Plasma Position

The magnetic pressure difference in toroidal confinement devices causes the plasma ring to expand outward unless a compensating force is applied to equilibrate the pressure.

Plasma positional equilibrium has been analyzed by Mukatov and Shafranov (1). The plasma column may be equilibrated by the use of a conducting shell or by imposition of external magnetic fields.

If the plasma column is surrounded by a conducting shell, any motion of the plasma will induce image currents in the shell that will in turn oppose the motion of the column. For a symmetrical plasma column surrounded by a perfectly conducting shell, the plasma displacement Δ_0 for equilibrium is given by equation (2.1).

(2.1)

where b is the shell radius, a is the plasma radius, r is the major radius of the torus, and l_i is the plasma internal inductance. Various additions to this simple theory to allow for gaps, slots and other

geometrical factors have been given in the literature by Shafronov, and Hosea (2). The fact that no shell will be perfectly conducting restricts the time scale over which the given solution represents reasonably accurate descriptions of the plasma behavior.

As long as the experiment time scale is short relative to the penetration time of the magnetic field into the shells, the image currents will be effective in constraining column displacements. The relevant penetration time is given by equation (2.2).

(2.2)

where σ is the conductivity, b the radius of the shell and d is the shell thickness. For large experimental machines this time will be on the order of one second, and pulse time will certainly be of the same order or longer. For this reason passive control will be inadequate and control by external fields is called for.

An externally applied magnetic field directed parallel to the major axis of the machine can be used to position the plasma. The motion is described in (2.3).

where D_0 is the displacement of equation (2.1), B is the applied external vertical field and B_b is the poloidal field produced by the plasma current evaluated at the plasma axis ($B_b = \frac{1}{2} \mu_0 I / b$).

2.2.1.2 Plasma Density in Tokamaks

Small adjustments in average plasma density appear to be possible through use of several density--related controls. The motivation for maintaining a constant plasma density is simplification of the analysis of the plasma behavior. If, however, the adjustments to average density result in changes in the plasma profile, the savings are not obvious.

Possible control mechanisms that suggest themselves are:

- 1) Slight adjustments in the vertical field strength also change the density. The amount of the adjustment is inversely proportional to the plasma major radius. The Princeton ATC tokamak has been designed to allow a relatively large range of major radius excursion. The device also alters the minor

radius in the same direction thus amplifying the potential range of density control.

- 2) Axial current adjustment provides both changes in the constraining field for free particles and the plasma temperature. Therefore, the net effect on density depends upon the details of the current adjustment.
- 3) A moveable limiter might be used to lower density.
- 4) The neutral beam heaters cause density increases (up to 10 to 20% on Ormak).
- 5) Initial setting of gas density in the toroidal container.

The plasma gross density can be sensed by application of several diagnostics including laser and microwave interferometry, Thompson scattering of laser light, and intensity measurements of bremsstrahlung.

The average "Z" in an experiment is a variable of interest. This could be controlled by the injection of He. It may also be possible to make the average Z a function of radius by injection of the He at the proper energy.

2.2.1.3 Control of Electron and Ion Temperatures

Control of the electron and Ion temperatures

2 during a plasma cycle is of interest for studies of
298 the electron-ion energy exchange rate under various
299 conditions. A particular value of the separation
300 between these two temperatures might possibly be
301 achieved by selective heating of one of the
302 particles. Cyclotron radiation at the cyclotron
303 frequency distribution or neutral beam injection at
304 resonant energies can be used to increase either
305 electron or ion temperature selectively. Ion
306 temperature is detected by sampling the neutral
307 exchange particle spectrum at the plasma container
308 wall, and electron temperature can be obtained from
309 broadening of scattered laser light, and measurements
310 of the ratio of x-ray intensity at two wavelengths.

312 2.2.2 Open Loop Controlled Variables

313 2.2.2.1 Plasma Density

314 2.2.2.2 Temperature

315 2.2.2.3 Vertical Field

316 2.3 Controlled State Variables--Start-up--Transient 317 Regimes

318 2.3.1 Closed Loop Controlled Variables

319 2.3.2 Open Loop Controlled Variables

320 2.4 Controlled State Variables--Shut-down

3 2.4.1 Closed Loop Controlled Variables

322 2.4.2 Open Loop Controlled Variables

323 2.4.3 Emergency Shut-down

2.5 Plasma State Control For Specific Machines

2.5.1 Fusion Machine #1

2.6 Plasma State Simulation for Control

3.0 PLASMA STATE CONTROL SUBSYSTEMS

3.1 Introduction

Heating and constraining of the plasma is accomplished by a group of separately operated subsystems including magnets, plasma heating devices and divertors. This section is concerned with the control problems originating within these subsystems. Instructions from a central plasma state controller to the subsystem calling for a particular output may require several controlled adjustments within the subsystem. These adjustments must be harmonized as well as controlled separately to insure proper function of the subsystem, and to insure that the desired effect on the plasma state is achieved.

3.2 Plasma Heating Systems

Several heating techniques involving widely differing instrumentation can be applied to tokamaks, however the major heating devices on these machines are expected to remain the ohmic heating transformer, and energetic neutral beam injectors. The discussion

of related control problems below is weighted accordingly. Other potential heating devices include relativistic electron beams, radio frequency generators, cyclotron frequency radiation generators, and magnetic shock heaters.

3.2.1 Neutral Beam Injectors.

A list of some of the large number of elemental controls required for neutral beam heaters is given below. Most are controlled by simple internal closed-loop systems.

3.2.1.1 ION Source (positive ion)

- a) arc current
- b) arc voltage
- c) gas pressure (flow rate)
- d) extractor voltage
- e) magnetic field current
- f) focusing electrode potentials, currents
- g) ion specie ratio
- h) extractor temperature
- i) coolant flow rate

3.2.1.2 Accelerator Section

- a) acceleration/deceleration electrode potentials
- b) beam position control
- c) pumping

37 d) electrole currents

379 3.2.1.3 Neutralization Cell

380 a) gas pressure

381 b) gas temperature

382 c) aperature temperatures

383 d)

384 3.2.1.4 ION Removal/Energy Recovery

385 a) ion deflection electrode

386 b) recovery electrode potential, current

387 c) ion/neutral ratio

388 d) beam position monitor

389 e) differential pumping

390 3.2.2 Other Heating Devices

391 3.3. Magnet Systems

392
393 3.3.1 Introduction

394
395 Magnets in fusion devices can be categorized
396 according to field strength and field variability.
397 We distinguish between three size ranges.

398
399 The "large" category is represented by the
400 toroidal field coils in tokamaks and stellarators and
401 the baseball currents in mirror machines. These
4 magnets are likely to be super conducting in the next
403 generation of experimental fusion devices. Because
404 of power supply limits and limits on the field

405 strength consistent with super conductivity, the
406 allowable variation upward of field strength in these
407 magnets will be small. The fields may conceivably be
408 adjusted between operating cycles, but the time scale
409 for such adjustments will depend upon power supply
410 capability.

411
412 In the second size category are the current
413 transformers in tokamaks and the Ioffe bar conductors
414 in some mirror machines. The fields here are of
415 intermediate size and therefore could allow more
416 variability. However, if these "magnets" are used
417 for plasma heating as well as constraining field
418 production then restrictions may be imposed on the
419 current levels. These devices are not likely to be
420 super cooled, and their currents except for possible
421 fine adjustments may be determined mostly by
422 pre-programmed open loop control.

423
424 The third category of magnets includes devices
425 whose fields may be controlled by dynamic feedback
426 over a relatively wide range of field strengths.
427 Included in this category are the vertical field
428 coils in tokamaks, the feed-back windings in theta
4 pinch machines, divertors, and magnetic limiters.
430 Time scales for the control of these magnets are
431 dependent on the field interaction with wall material

in the fusion machines. Closed-loop dynamic feedback
for these magnets is generally proposed.

3.3.2 Major Confinement Field Magnets

3.3.2.1 Super Cooling Problems

3.3.2.2 Power Supply

3.3.2.3 Start-up and Shut-down Control

3.3.3 Plasma Current Transformer

3.3.3.1 Current--Density Relationship

3.3.3.2 Programmed Currents

3.3.3.3 Active Control Issues

3.3.4 Perturbation Fields

3.3.4.1 Vertical Field Control

3.3.4.2 Divertors

3.3.4.3 Magnetic Limiters

3.3.5 Energy Recovery System

3.4 Divertor System

3.4.1 Pumping System

3.4.1.1 Rate Control

3.4.1.2 Diagnostic Feedback

4.0 PLASMA DIAGNOSTIC CONTROL

4.1 Introduction

If plasma behavior invariably followed prediction there would be little need for diagnostic devices except for feedback situations. However an important portion of the learning-by-experiment

process involves the failure rather than confirmation of predictions. In this situation accurate and responsive diagnostic devices are especially important.

The control problem in diagnostic devices involves two areas, namely, control of the elements of each device to insure proper functioning, and the processing of the measurements. Diagnostic devices may be complex systems themselves. An example is a multichannel laser and its associated sensory array. If a diagnostic device is used in a feedback control loop problems of response time and the insertion of intermediary calculations arise. The raw measurements of several diagnostics may need to be entered in an iterative solution to simultaneous equations to produce complete plasma state information.

Control problems related to specific diagnostic devices and their relationship to other diagnostic and experiment subsystems are discussed below.

4.1.1 Relationship to State Control

4.1.1.1 Accuracy

4.1.1.2 Response Time

4.1.2 Computational Control

486	4.1.3 Operational Regime Considerations
487	4.2 Temperature Sensing
488	4.2.1 Bremsstrahlung Detectors
489	4.2.1.1 Power Supply
490	4.2.1.2 Amplifiers
491	4.2.2 Laser Scattering
492	4.2.2.1 Laser Status
493	4.2.2.2 Power Supply
494	4.2.2.3 Detectors
495	4.3 Density Sensors
496	4.3.1 Microwave Interferometry
497	4.4 Position Sensors
498	4.4.1 Laser
499	4.4.2 Magnetic Probes
500	4.4.2.1 Amplifier
501	5.0 EXPERIMENT CONTROL AND DATA ACQUISITION SYSTEMS
502	5.1 Introduction
503	5.1.1 Scope of Problem
504	5.2 Aims of Experiment Control
505	5.2 Presetting Plasma State
506	5.3 Preset Output Selection
507	5.4 Automated Start-up and Shutdown
508	5.3 Data Acquisition and Display
509	6.0 PLANT SUPPORT SYSTEM CONTROL
5	6.1 Introduction
511	6.1.1 Large Facility Control
512	6.2 Power Supply System

511 6.2.1 Multivoltage Controls

514 6.2.2 Energy Recovery

515 6.3 Coolant System

516 6.3.1 Liquid Nitrogen

517 6.3.2 Helium

518 6.4 Vacuum System

519 6.5 Fuel Maintenance

520
521 5.0 Experiment Control And Data Handling

522
523 Control of the entire experimental operation
524 falls naturally into a hierarchy of control levels.
525 At the top of this sequence is an experiment overview
526 controller that maintains awareness of the state of
527 the whole experimental facility. It monitors the
528 readiness of each subsystem including plant systems
529 such as the coolant and vacuum systems, and plasma
530 state controlling subsystems like heaters and
531 magnets. Plant safety functions are controlled by
532 this processor. Other tasks of this processor are to
533 check its own proper function, to test the plasma
534 state control processor, and to insure the readiness
535 of the data acquisition system. This processor would
536 fill an enabling role for the plasma state control
537 processor, i.e., it would permit an experimental
538 cycle begin after ascertaining complete system
539 readiness.

541 At the second control level is the plasma state
542 control processor. This controller creates the
543 plasma, maintains it over the plateau regime, and
544 shuts it down. It operates open loop, preprogrammed
545 state shaping, and closed loop state shaping using
546 dialable state values and diagnostic feedback. A
547 number of calculations relating to plasma state
548 element relationships will be done by this processor
549 in near real time. Calculations relating raw
550 diagnostic data to plasma state values will be done
551 in parallel to these.

553 At the third control level are the controllers
554 for the various subsystems. These are probably
555 hardwired computers whose function is to coordinate
556 all the elements of a subsystem to achieve a state
557 alteration requested by the plasma state controller.

559 The data display and aquisition system fills
560 many experimental functions. It displays the central
561 processor readiness information, it shows
562 experimental progress during and after the run cycle,
563 and it compiles data from the experiment in hard copy
5 form.